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# **Assessment Study of the State of the Art in Adaptive Control and its Applications to Aircraft Control**

by

**Howard Kaufman  
ECSE Department  
Rensselaer Polytechnic Institute  
Troy, NY 12180  
email: kaufmh@rpi.edu  
Tel: 518 276 6081  
Fax: 518 276 6261**

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## Summary

Many papers relevant to reconfigurable flight control have appeared over the past fifteen years. In general these have consisted of theoretical issues, simulation experiments, and in some cases, actual flight tests. Results indicate that reconfiguration of flight controls is certainly feasible for a wide class of failures.

However many of the proposed procedures although quite attractive, need further analytical and experimental studies for meaningful validation. Many procedures assume the availability of failure detection and identification logic that will supply adequately fast, the dynamics corresponding to the failed aircraft. This in general implies that the failure detection and fault identification logic must have access to all possible anticipated faults and the corresponding dynamical equations of motion. Unless some sort of explicit on line parameter identification is included, the computational demands could possibly be too excessive. This suggests the need for some form of adaptive control, either by itself as the prime procedure for control reconfiguration or in conjunction with the failure detection logic.

If explicit or indirect adaptive control is used, then it is important that the identified models be such that the corresponding computed controls deliver adequate performance to the actual aircraft. Unknown changes in trim should be modelled, and parameter identification needs to be adequately insensitive to noise and at the same time capable of tracking abrupt changes.

If however, both failure detection and system parameter identification turn out to be too time consuming in an emergency situation, then the concepts of direct adaptive control should be considered. If direct model reference adaptive control is to be used (on a linear model) with stability assurances, then a positive real or passivity condition needs to be satisfied for all possible configurations. This condition is often satisfied with a feedforward compensator around the plant. This compensator must be robustly designed such that the compensated plant satisfies the required positive real conditions over all expected parameter values. Furthermore, with the feedforward only around the plant, a nonzero (but bounded error) will exist in steady state between the plant and model outputs. This error can be removed by placing the compensator also in the reference model. Design of such a compensator should not be too difficult a problem since for flight control it is generally possible to feedback all the system states.

It is also important to note that multiple model based approaches are very attractive in terms of their potential speed of response to abrupt changes and/or failures. However unless some tuning is present, an extraordinary number of models may be required.

In view of the advantages offered by direct adaptive control and multiple model based control, it is anticipated that the combination of these methods should be very effective for reconfigurable

flight control systems. Associated with each of the multiple models would be a controller and possibly a reference model. Such controllers would be designed apriori so that the response of the corresponding control loop would display desired handling qualities and at the same time be relatively robust over a reasonable range of plant uncertainty. Different reference models associated with each aircraft configuration model would allow the specification of changed performance requirements in the presence of failures. The adaptation procedure can then either be designed to retune the controllers because of mismatch between the selected aircraft model and the actual dynamics, or the adaptive controller might be designed to adjust the input applied to the closed loop defined by the aircraft and the selected controller. With enough selectable models and associated tunable controllers that are adequately robust, it is anticipated that the resulting reconfiguration will be implementable, adequately fast and such that the performance goals are satisfied.

## 1.0 Introduction

Adaptive controllers have the capability for both recognition of the occurrence of a system change and the appropriate modification to the controller itself so that the response characteristics are preserved. Adaptive control has been studied extensively in the past for flight control applications by many investigators. However such applications have for the most part considered adaptation of the controllers to account for system modeling uncertainties, nonlinearities, and the dynamic effects caused by changes in mach number and altitude. In these cases, the scenarios did not consider an abrupt change in system configuration that might without immediate intervention, lead to instability. The importance of being able to maintain acceptable control in the presence of such changes is evident from the activities of NASA's Intelligent Damage Adaptive Control System (IDACS) program and the recent workshops on Reconfigurable Systems for Tailless Fighter Aircraft (RESTORE) held at Wright Patterson Air Force Base (WPAFB). A description of the RESTORE program and its accomplishments may be found in the 1998 AIAA paper by Brinker and Wise [11].

Abrupt system changes can result from failures, weather effects, and pilot inattention. Aircraft accidents have in the past, resulted from the failure of one or more actuators and/or sensors and from sudden changes in the aerodynamic characteristics. Actuator failures might be caused by electrical and/or mechanical problems, hydraulic line damage caused by debris breaking away from the aircraft, fatigue, and air frame structural damage. Sensor failures might be caused by device failures. Aerodynamic changes might be caused by icing, engine failures, physical engine separation, and structural damage.

In many such cases, it is probable that the aircraft remains controllable, although with response characteristics unfamiliar to the pilot. Thus it is important that some type of control compensation be incorporated that can assist the pilot to safely maneuver the damaged aircraft. In some cases, it may even be desirable to have the controller override the pilot's commands. The feasibility of such a procedure was demonstrated in 1997 by Burken and Burcham [12] who discussed results of flight tests on a large civilian multi-engine transport, the MD-11 in which only engine thrust would serve as backup to the primary flight control system. Results showed that this thrust backup system could be used in the presence of certain major failures (eg hydraulic pressure loss), for landing the airplane without the aid of the aerodynamic control surfaces.

Therefore it is of interest to develop a system that quickly recognizes and then compensates for a sudden change in the aircraft capabilities and/or a change in the response characteristics. This recognition should be followed by a damage assessment in terms of controllability, a development of requirements with respect to mission changes (e.g., to an immediate landing), specification of changes in the actuator armamentarium, designation of useable sensors, and appropriate modifications to the control algorithms.

Relevant to these requirements are the concepts of reconfigurable control and reconstructable control [51]. Although in many cases these terms have been and are being used interchangeably,

there are distinctions based upon the degree of pre-planning. When the controls are designed apriori to accommodate anticipated failures, then these are designated as reconfigurable; however, if the controls are to accommodate unanticipated failures, then the term reconstructable is appropriate.

With regard to the need for such control modifications, many investigators have considered the feasibility of the accommodation to specific types of damage or failures and the potential of using some sort of adaptive control for the implementation. Both explicit (or indirect) and implicit (or direct) adaptive controllers have been considered. Explicit adaptive controllers require the use of an (explicit) online parameter identifier for tracking the actual aircraft parameter changes. Such online tracking is of course subject to the tradeoffs between the needs for a short memory for rapid tracking and a long memory for noise reduction. Implicit adaptive controllers monitor the system behavior and directly adjust the controller parameters (gains) without the explicit use of a parameter identifier. In both cases the adaptation needs to be sufficiently rapid in order to maintain desired performance specifications during the failure accommodation.

In many cases, input has been included from a higher level fault diagnosis and/or failure detection and identification system that both recognizes the existence of a problem and identifies the source of the problem (eg from a sudden sensor and/or actuator failure). This would immediately designate the need to consider a revised set of actuators and/or sensors and thus avoid the slower process of online identification.

Validation of the various proposed reconfiguration control algorithms has been performed using linear models, nonlinear models, and in some cases actual flight tests. Clearly response time is an important factor for successful controller reconfiguration.

Taking into account the need for rapid controller adjustment in response to failures and/or rapid parameter variations, it is important to consider and to assess the potential role of adaptive control. In fact in a recent paper, Pachter and Chandler [53] state that "adaptive control affords the accommodation of a high level of uncertainty." They then go on to state that reconfigurable control should be used in the presence of dynamic and abrupt unknown parameter changes. To this effect, a review of the existing literature on reconfigurable controls is contained in Section 2.0. An evaluation of this previous work is presented in Section 3.0, and validation procedures are then presented in Section 4.0. Finally conclusions and recommendations for future research efforts are discussed in Section 5.0.

## 2.0 Literature Review

### 2.1 Overview

Over the past 15 years, many investigators have studied various aspects of reconfigurable and/or reconstructable aircraft control systems. Many of these control procedures used adaptive algorithms for alleviating the effects of failures and rapid parameter changes. In general these adaptive procedures used online explicit parameter identification or model following principles for fault accommodation. As an alternative, other approaches have utilized explicit fault diagnosis and/or failure detection and identification logic for defining the new model structure and/or parameter set, which would subsequently be used for control redesign. In many cases, the fault diagnosis and adaptation functions have been combined through the use of a bank of multiple models, or through the use of fuzzy logic, intelligent control, and/or neural networks.

The importance and feasibility of reconfigurable control was pointed out in 1995 by Wise [64], who cited three main problems to be considered; namely, real time identification, real time control computation, and digital implementation. He also discussed successful flight tests conducted under the joint Air Force and NASA program, Self Repairing Flight Control System (SRFCS). These tests showed the potential of reconfigurable/damage adaptive flight control laws for recovery from failures. He also cited the ongoing work at Barron Associates [46,63], where adaptive algorithms were being evaluated by flight test for a variety of simulated failures (e.g. missing flap, missing half tail surface, partially missing rudder, missing half tail and rudder).

Also of importance to the overall issue of validation of reconfigurable aircraft controls, is the 1997 paper by Burken and Burcham [12]. They report on flight test results on a large civilian multi-engine transport, the MD-11. The control system for this aircraft was modified so that only engine thrust would serve as backup to the primary flight control system. Results showed that the backup system could be used in the presence of certain major failures (e.g. hydraulic pressure loss), for landing the airplane without the aid of the aerodynamic control surfaces.

An overview of research on various aspects of reconfigurable flight control is presented in the next four sub-sections. Section 2.2 considers procedures that directly require some sort of explicit fault diagnosis and/or failure detection and identification procedure in conjunction with a control algorithm. Because of the large number of possible faults that can arise, a comprehensive fault detection scheme can be computationally prohibitive. Thus as an alternative to using fault diagnosis logic, sections 2.3 and 2.4 respectively discuss literature relevant to the usage of explicit (indirect) adaptive control procedures and implicit (direct) adaptive control procedures. Section 2.5 then discusses multiple model based procedures that in a sense combine rapid failure detection with adaptive control. Finally Section 2.5 presents reconfigurable controllers that have been designed with neural nets, fuzzy concepts and/or intelligent control procedures.

## 2.2 Reconfiguration using failure detection/fault diagnosis

Reconfiguration procedures have been proposed that are dependant upon having available some higher level fault diagnosis/failure detection and identification logic that defines a model for the aircraft dynamics following some abrupt physical change. A general survey of procedures for detecting changes is given by Basseville in [5]. It is of interest to note that in some cases this logic is coupled with some sort of system parameter identification. More recently in 1998, Gopisetty and Stengel [27] presented parity space and parameter estimation methods for detection and identification of sensor and actuator failures in flight control systems.

A study of the potential of using reconfigurable controls to accommodate failures was presented by Ostroff and Hueschen [52] in 1984. In 1988 Caglayan et. al. [13,14] described a hierarchical failure detection, identification, and estimation (FDIE) algorithm for use in a self-repairing flight control system. Coupling of such FDIE procedures with a procedure for adjusting the controls accordingly defines a reconfigurable control system. Since 1985 various papers have appeared that discuss controllers that might be coupled to such an FDIE system for flight control reconfiguration.

A paper by Ostroff [51] in 1985 showed how reconfiguration might be accomplished by coupling failure detection with least squares matching of the closed loop system transfer functions. This required the pseudo inverse of the control and output matrices. Although this procedure was validated using nonlinear simulation tests, no supporting analytical stability results were presented. In 1988, Caglayan and his co-investigators [13,14] also discussed a pseudo-inverse based re-adjustment of control gains so that the closed loop matrices would be preserved in a least squares sense. Their algorithm was evaluated using a nonlinear simulation of a Grumman CRCA with surface damage. Although results were positive, stability was not guaranteed, and problems could result from saturation effects. A stability analysis of such pseudo-inverse based procedures was presented by Gao and Antsaklis [24] in 1991. They proposed a new approach valid for a certain class of structured uncertainties; however, no extensive flight control evaluation studies were presented. In [21,24], Dhayagude, Gao, and Antsaklis evaluated the validity of applying pseudo-inverse methods with model following procedures in the presence of aircraft changes. However they did not include any results corresponding to a coupling of fault diagnosis with their control restructuring procedure.

Optimal control based procedures have also been considered for reconfiguration assuming the existence of a higher level failure detection and identification algorithm. In 1985, Looze et. al. [40], proposed a procedure for re-adjusting the performance index weights so as to maintain system specifications even in the presence of a failure. Their evaluation used a linear simulation of a 737 with rudder failure. More extensive simulations however should be considered for this approach with different surface failures as well as sensor failures. In 1989, Moerder et. al. [45] used failure detection in conjunction with linear quadratic gaussian controllers on linear simulations of the AFTI F16 with a variety of failed surfaces. Although results were favorable, more validation is needed on nonlinear models. The adjustment of performance index weights was also considered in 1990 by Huang and Stengel [29], who considered the optimization of model following indices. With linearized lateral F4 motion, they were able to show that such weight modification was feasible in the presence

of aileron surface loss and decrease in control effectiveness. However this was not tested with any fault detection or adaptation logic. Another linear optimal procedure was proposed in 1991 by Ahmed-Zaid et.al. [2]. Although failures were considered, the procedure was primarily for single input single output systems.

Various other procedures have also been proposed for use in conjunction with a failure detection and identification algorithm. An eigenstructure procedure to account for changes from operating conditions was presented in 1994 by Jiang in [31]. Because failures were not explicitly considered, it is difficult to assess stability and timing problems that may arise. In 1995 Wu [66] applied fuzzy sets with Mu-synthesis to a linear pitch axis controller in the presence of canard failure. However this study was very limited in scope and was more of theoretical interest. Finally in 1998, Huzmezan and Maciejowski [30] considered model based predictive control with fault detection for single input single output missile dynamics. Although they did not consider aircraft dynamics, their approach might be relevant if timing is not an issue. More recently Shearer and Heise [57] applied model predictive control to a simulation of the nonlinear dynamics of an F-16 aircraft. Although results were promising, more research is needed to address topics such as tuning, adaptation, model simplification, and pilot modelling.

### **2.3 Reconfiguration using explicit or indirect adaptive control**

As an alternative to using some type of failure detection logic, the concept of online parameter identification offers the possibility of tracking both continuous and sudden changes in the system dynamics. As these changes are identified, the adaptive control logic is used online for appropriate modification of the controller parameters (e.g., gains) so that acceptable handling qualities are preserved even in the presence of failures. With the use of explicit parameter identification, it is often necessary to provide adequate external excitation in order to insure acceptable parameter estimates. This excitation needs to be acceptable to the pilot and at the same time large enough to counteract the effects of noise. A further concern is the need to identify a system under closed loop control. Without sufficient excitation and/or previous knowledge, such closed loop identification can only be capable of computing estimates of parameter combinations rather than individual estimates. These problems might be somewhat alleviated by recent results presented by Elgersma, Enns, and Shalton on signal injection [22], and by some recent results on closed loop identification by Feng et. al. [23].

Chandler et.al. [16,17,18,19] and Pachter et.al. [54,55] have published many papers that deal with various aspects of online aircraft parameter identification for reconfigurable controls. They evaluated moving window based identifiers and coupled them with linear quadratic regulators, predictive controllers, and even online optimizing Hopfield networks. These adaptive controllers were then applied to linear simulations of an F-16 with disturbed trim and 50% loss in horizontal tail area. Results to date indicate that the proposed identification procedures should be very effective for tracking aircraft changes. Some work in combining identification with feedback linearization has been reported by Ochi and Kanai [50]. Although their paper lacks details concerning the algorithm, the results on a six degree of freedom nonlinear fighter model look very promising. Bodson et. al. [7,8,28] have considered model following control with a modified sequential least squares based online identifier that combines a fading factor with a penalty on parameter changes. A constant



disturbance term was also identified to model unknown trim changes. Very good results have been reported for simulations with nonlinear dynamics and a locked left horizontal tail. Because reconfigurable controllers must account for constraints on actuator rates and positions Bodson and Pohlchuck in 1998 presented four approaches for limiting the commands to a reconfigurable controller [6]. In view of the excellent tracking delivered by Bodson's modified sequential least squares identifier, it also has been used by Ward et. al. [46,63] with a receding horizon predictive controller. These studies, possibly the most extensive to date, consisted of simulation studies, piloted simulation studies, and actual flight tests. Failures included the left horizontal tail, the right horizontal flaperon, partially missing rudder, and missing half tail and rudder. Results showed the feasibility of using explicit adaptive control for reconfiguration and improved aircraft survivability.

## **2.4 Reconfiguration using implicit or direct adaptive control**

Although to date most of the research in adaptive control for aircraft controller reconfiguration, has considered indirect methods that require explicit on line parameter identification, some consideration has been given to direct procedures which in a sense directly estimate or adjust the controller gains without the use of explicit aircraft parameter estimates. In general these procedures are based upon the use of a forced reference model whose output is to be tracked by the process (aircraft) output. If all the states of the plant are to track all the states of the reference model, then the so called conditions for perfect model following must be satisfied [34]. All states must then be available for feedback or an observer must be incorporated. If however, only the plant output (usually of lower dimension than the state vector) is to track the model output, then the less restrictive so-called command generator tracker procedure may be used to develop the adaptive controller [34]. Although the controller is easily implemented, certain positivity or passivity conditions must be satisfied to assure stability. Procedures based upon feedforward compensators have been developed to alleviate these conditions [34].

The attractiveness of this approach for reconfigurable controls was pointed out by Morse and Ossman [47]. They used a simulation of linearized AFTI/F-16 dynamics in the presence of single surface failures (horizontal tail, rudder, flaperon), double sided failures (double flaperon, rudder and canard, double horizontal tail, same side flaperon and horizontal tail) as well as some triple and quadruple failures. Results were very encouraging and certainly indicative of the potential for applying direct adaptive control to aircraft reconfigurable control systems. However, additional work is needed to address some of the more recent theory related to the alleviation of the passivity conditions [32,33] required for stability assurance. Incorporation of feedforward compensation around both the aircraft and the reference model should enable the satisfaction of these passivity conditions and at the same time ensure perfect output tracking [34]. Further testing should also consider the use of more representative nonlinear aircraft equations of motion.

## **2.5 Reconfiguration using multiple model based procedures**

Adaptive flight control based upon a bank of switchable models was proposed by Athans et. al. [3] in 1977 as a means for improving the transient response of adaptive systems especially in the presence of abrupt variations. The control was computed as the weighted sum of the linear-quadratic

gaussian controllers corresponding to each of the models. The weights were the associated conditional probabilities as computed by Kalman filters. More recently in 1994, Narendra and Balakrishnan [49] considered the problem of multiple model based model reference adaptive control. They used multiple adaptive identification models to identify a plant and then the adaptive controller corresponding to the identified plant with the smallest performance index. In 1997, Narendra and Balakrishnan [48], proposed further switching and tuning schemes that combined both fixed and adaptive controllers. Their favored approach consisted of a bank of fixed models, with one free running adaptive model and one reinitialized adaptive model

With regard to recent applications of multiple model controllers to flight systems, Maybeck et.al. [41,42,44] used multiple models with no adaptation for alleviating the effects of hard and soft actuator and sensor failures. They considered a nonlinear simulation of a Vista F-16 with failures in the stabilators, flaperons, rudder and sensors for velocity, angle of attack, pitch rate, normal acceleration, roll rate, yaw rate, and lateral acceleration. This approach required many models and was very effective for hard failures. Results for soft failures were best when effectiveness had been reduced below 50%. Rauch in [56] considered a reconfiguration using multiple models and fuzzy logic. However, this was mainly an idea tried out for ship motion without any attention given to aircraft. More recently Boskovic et. al. [9,10] and Mehra et. al [43] combined multiple model switching with adaptive model following control principles and considered simulations of a tailless advanced fighter aircraft with wing damage and control effector failures. Results did indeed demonstrate the effectiveness of this procedure. Because all states of the plant were forced to follow all states of the reference model, it was necessary to assume the validity of the so called conditions for perfect model following and to use observers for estimating the full state vector. This need for observers should be alleviated through the use of a bank of output model reference adaptive controllers.

## **2.6 Reconfiguration using neural networks, fuzzy concepts, and intelligent control**

Reconfigurable control can often be cast as a hierarchical problem requiring some sort of supervisory and/or intelligent control overseeing the detection and modification layers. Thus the use of intelligent control, neural networks, and fuzzy control has been considered for one or more of the reconfigurable functions. In [61,62], Stengel discussed intelligent fault tolerant control in general and specifically for flight control systems. Kwong et. al. [38] used fuzzy model reference learning control [39] for an F-16 simulation with failures in aileron or rudder. However there were no considerations given to timing, stability and robustness. A theoretical analysis of using fuzzy sets for controller selection was considered by Wu in [67]. However its application to flight control seems unclear. Copeland and Rattan [20] considered the use of fuzzy control as a supervisor for reconfigurable control. This paper however lacks details and does not address stability and timing issues. Barron in [4] considered the use of neural networks for fault detection using flight simulations; however, control reconfiguration was not considered. Rauch in [56] discussed reconfiguration using multiple models and fuzzy logic but for ship, not flight applications. Chandler et. al. [16] in 1993 reported on the use of Hopfield networks for optimizing a model following penalty

function given the identified parameter estimates; however, the procedure is at present too computationally intensive for real time use. Finally in a recent paper [15], Calise, Lee, and Sharma discussed the use of adaptive neural nets for modification (as opposed to the entire computation) of the control signal in the presence of failures. The neural network was used to compensate for the inversion error between the baseline control law's model and the true system model. Differences between these models can arise from uncertainties and/or failures and damage. Results to date have considered the simulation of a tailless fighter with locked left aft-body flap. Although these results appear to be quite good, more evaluations are needed for validation.

a transfer function that satisfies the positivity conditions. Also based upon the work reported by Bodson [7,8], it is also recommended that a constant (but unknown) disturbance be included in the plant equations to account for unknown trim.

The multiple model based approaches discussed in Section 2.5 are very attractive in terms of their potential speed of response to an abrupt change and/or failure. However unless some online tuning is present, an extraordinary number of models may be required. With this in mind, the procedures discussed by Boskovic et. al. [9,10] and Mehra et. al. [43] seem very promising for reconfigurable controllers. This approach which combines multiple models, switching, and tuning appears to be robust in the presence of severe effector failures. However as noted in Section 2.5, an observer is required since full state feedback is required. Thus it is recommended that direct output model following be incorporated (as discussed in Section 2.4) as the control algorithm to be coupled with multiple model based switching. In addition it is suggested that switching also be used to select reference model dynamics that are more representative of the failed aircraft capabilities. This follows since a pilot aware of reduced capabilities will not be as demanding in command following expectation. It is further suggested that the algorithm also be extended to include sensor failures as well as actuator failures.

Finally with regard to reconfiguration using neural networks, fuzzy concepts, and intelligent control, neural networks could as in [15] be useful for generating a signal that modifies the control signal to accommodate to a change or failure. Because of stability issues, this procedure is preferable to the direct use of a neural net for computing the entire actuator command. Other possible uses of neural networks are for the detection of failures and in the development of online models of the aircraft dynamics.

## 4.0 Validation Procedures

To date the explicit adaptive control procedure described in [46] and [63] has received the most extensive validation. This has consisted of linear simulations, nonlinear simulations, piloted simulations, and actual flight tests. Various other procedures have been tested with only one or two simulated failures, while many others have been tested with a wide class of simulated sensor and actuator failures.

Because theoretical results have for the most part only addressed the stability of the algorithms as applied to linear aircraft motion with analytically modelled failures, it is very important that nonlinear simulation and/or analysis be considered. Recent results in the concept of backstepping might be considered for the stability analysis of the various reconfigurable algorithms when applied to nonlinear models.

In any event it is important that the controller be analytically shown as stabilizing for the linear models for the normal and for the various failed representations. This analysis should of course be followed by more representative simulation studies using nonlinear system models and then actual flight tests.

With regard to the types of failures to be considered, consideration should be given to flight control surface failures, damage to lifting surfaces, and sensor failures. Representative control surface failures should include locked and floating rudder, aileron, and elevator. Damage should be modelled as a reduction in control effectiveness for a wing flap and/or the rudder. Representative sensor failures should include those that measure velocity, angle of attack, pitch rate, yaw rate, lateral acceleration, and normal acceleration.

## 5.0 Conclusions and Recommendations

Based upon the existing literature, it does indeed appear that it is possible to design and implement reconfigurable controllers for both commercial and military airplanes. This conclusion is based upon stability analysis, simulation experiments, and actual flight testing. It is also supported by the results in the 1997 paper by Burken and Burcham [12], who showed that a large civilian multi-engine transport, the MD-11 could be controlled with only engine thrust as backup to the primary flight control system. Results showed that this backup system could be used in the presence of certain major failures (e.g. hydraulic pressure loss), for landing the airplane without the aid of the aerodynamic control surfaces.

Common to much of the reported research in reconfigurable control design, is the use of controllers based upon model following principles. Such indices have been used for direct adaptive control [47], indirect adaptive control [6,7,8,28,46,63], multiple model control [9,10,43], variable structure control [35], and in neural network based control [15]. Thus it is recommended that the use of such indices be continued in subsequent research or at the very least be used as bench marks for comparative testing.

Taking into account that the allowable time for full control reconfiguration might be two to four seconds for a commercial airplane and fractions of a second for a military aircraft, it is important to stress those procedures that will be adequately fast with sufficient guarantees of stability. As stated in Section 2.0, Pachter and Chandler in a recent paper [53], recommend adaptive control in situations where there is a high level of uncertainty and when there are abrupt changes in unknown parameters. In particular, Pachter and Chandler recommended the use of outer-loop explicit adaptive control as opposed to existing inner loop procedures. However since explicit adaptive controllers have already received considerable attention for reconfigurable control design, it is recommended that direct model reference adaptive controllers be considered in future research. Direct adaptive controllers have the potential of delivering a faster response to a configuration change compared with explicit adaptive controllers. This follows because no explicit online parameter identifier needs to be executed. The adaptive outer-loop recommendations of [53] can be accommodated if the inner-loop consists of the aircraft and an adequately robust control compensator. The direct adaptive algorithm would then be used as an outer-loop controller designed so that the inner-loop output tracks the reference model output. It is anticipated that satisfaction of the sufficiency conditions for this closed loop configuration will be less demanding than for the open loop aircraft dynamics.

Furthermore, as previously noted, direct adaptive controllers can easily be combined with multiple model based procedures for even faster time response. Associated with each of the multiple models would be an adaptive controller and possibly a reference model. Such controllers would be designed apriori so that the response of the corresponding control loop would display desired handling qualities and at the same time be relatively robust over a reasonable range of plant uncertainty. Different reference models associated with each aircraft configuration model would allow the specification of changed performance requirements in the presence of failures. The adaptation procedure can either be designed to retune the controllers because of mismatch between the selected aircraft model and the actual dynamics, or the adaptive controller might be designed to adjust the

input applied to the closed loop defined by the aircraft and the selected controller. In either event, the combination of a tunable controller with multiple model based switching should reduce the number of models that would be needed if only fixed controllers were to be used. With enough selectable models and associated controllers that are adequately robust [1], it is anticipated that the resulting reconfiguration will be implementable, very rapid and will meet the performance goals.

Issues that need investigation include:

The inclusion of a constant plant disturbance vector to account for unknown trim

The design of a representative bank of aircraft models that allows rapid switching and adequate control loop robustness

The design of reference models that are indicative of performance goals for each of the failed configurations

Development of procedures that assure satisfaction of the passivity conditions over all anticipated configurations

Development of robust-inner loop compensators that can be used in conjunction with adaptive outer-loop controllers. Of potential interest to such a design are recent results in variable structure control for aircraft [35,58], linear matrix inequality based flight control design [65], and *H-infinity* based fault tolerant design [26].

Although it should be possible to validate stability for the linear representations, it may be necessary to rely on simulation studies for more representative nonlinear models. However, recent results in the concept of backstepping [37] and its applications to aircraft control [60] might be useful for the stability analysis of certain nonlinear models controlled by the reconfiguration algorithms.

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